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A comparison of natural and restored salt marsh vegetation and soil characteristics

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ABSTRACT

A COMPARISON OF NATURAL AND RESTORED SALT MARSH VEGETATION AND SOIL CHARACTERISTICS

by Michiko Taniguchi

Quantitative studies assessing the structural and functional similarities of restored salt marshes to natural ones should aid regulatory agencies in determining if marsh restoration is an acceptable mitigation for human-caused marsh destruction. This research assesses the similarities of two types of San Francisco Bay restored marshes, breached and culverted, to natural reference sites by measuring vegetation and soil characteristics. All of the restored marshes studied were significantly different from their natural references in either soil or vegetation characteristics. The stem density, average height of stems, and total stem length were greatest in the natural marshes. Two breached marshes showed the greatest similarity to their natural references as there was no significant difference in 5 of the 7 parameters measured. Although there was variability in conditions contributing to plant density, height and total stem length, significant factors influencing vegetation growth at the study sites included salinity, nitrogen concentrations, and marsh age.

ACKNOWLEDGMENTS

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Background and Introduction

The San Francisco Bay estuary is the largest estuary on the west coast of the United States (San Francisco Estuary Project 1991), and two-thirds of the Pacific coast's salt marsh and tidal mud flats are located here (Josselyn et al. 1990). Most of the estuary's historic tidal marshes have been significantly altered or no longer exist, and threats to the remaining wetlands continue (San Francisco Estuary Project 1991). Approximately 95% of the San Francisco estuary's tidal marshes have been diked or filled since the Gold Rush of 1849 (Atwater et al. 1979). In the south San Francisco Bay, about 83% of historic tidal marshes were reclaimed for salt production by the 1930's (San Francisco Estuary Project 1991). Additional human activities that have led to the loss and degradation of the San Francisco Bay estuary's wetlands include reclamation, hydraulic mining and sediment deposition, water diversions, agriculture and salt production, flood control, transportation and navigation facilities, resource extraction and urbanization (Atwater et al. 1979).

Salt marshes and their related habitats are considered to be some of the Bay's most valuable natural resources. These wetlands provide habitat for hundreds of species of fish, birds and other wildlife. They provide other valuable functions such as water quality improvement, flood protection, shoreline anchoring, open space, and recreational opportunities. Wetlands are also believed to be among the most productive ecosystems on earth (San Francisco Estuary Project 1991). Salt marsh productivity is a key component of the overall function of the San Francisco Bay ecosystem. The high yield of plant material is useful both within the marsh and in the estuary, as it fuels the food chain. Within the marsh, the vegetation is utilized by epifaunal invertebrates, insects and waterfowl, which directly graze on the vegetation for food. Most of the plant material, however, dies and gets washed out of the marsh into the estuary or is utilized within the marsh for a number of microbial processes, including decomposition and nitrogen fixation. The decomposed plant material provides food for filter feeders and stimulates algal growth, which is used by grazing epifauna and detritovores. Detritus and benthic organisms attract and provide food for a variety of fish and birds (Josselyn 1983). However, diking and filling of historic tidal marshes have decreased the productivity of the Bay ecosystem, as nutrient and organic matter supplies have been cut off with the elimination of tidal exchange between the Bay and the marshes. Restoration of diked areas to tidal action is believed to increase the productivity of the Bay as well as attract and support an increase in wildlife (Wakeman 1982).

The decline in quantity and quality of tidal salt marshes in the San Francisco Bay area has increased the importance of providing habitat for specifically adapted wildlife species. In the San Francisco Bay area, tidal salt marsh species have become threatened with extinction, including the salt marsh harvest mouse (*Reithrodontomys raviventris*), which inhabits the upper marsh pickleweed (*Salicornia* spp.) areas, and the California clapper rail

(*Rallus longirostris obsoletus*), which inhabits the lower intertidal and channel areas.

Pacific cordgrass (*Spartina foliosa*) is the dominant species found at the lower intertidal elevations between Mean Tide Level and Mean High Water (MTL-MHW) in the San Francisco Bay tidal salt marshes. Near MTL it forms pure stands, but it intermingles with pickleweed (*Salicornia virginica*) between MTL and Mean Highest High Water (Atwater et al. 1979). At the lower margin of *S. foliosa*, the maximum daily submergence reaches as much as 21 consecutive hours when two high tides are separated by a low water that is not low enough to expose the lowest level of *S. foliosa* growth (Hinde 1954). It has a vertical range of about 1.0 meter.

The lower limit of *S. foliosa* is thought to be controlled by tidal inundation (Hinde 1954), while the upper limit is believed to be controlled by salinity (Mahall and Park 1976). Height and biomass of plants growing in the upper limits of the marsh are generally less than the plants growing at lower intertidal elevations (Atwater and Hedel 1976). Although *S. foliosa* will continue to grow at reduced rates at salinities as high as 39.5 ppt (Mahall and Park 1976), it grows best at salinities less than 15 ppt (Cain and Harvey 1983). Greenhouse experiments have shown that *S. foliosa* prefers fresh water (Phleger 1971); however, it is restricted to areas with soil salinities greater than 15 ppt (Atwater and Hedel 1976). Because *S. foliosa* is replaced by other species which are believed to compete successfully against the cordgrass, it is absent in the fresher water marshes in the upper reaches of the San Francisco Bay estuary. *S. foliosa*'s areas of competitive advantage are thus confined to the lower reaches of the estuary, perhaps because potential competitors are physiologically excluded by high water and high soil salinities (Atwater and Hedel 1976).

Spartina foliosa, a perennial grass, has an average stem diameter of 1.5 cm at the base (Callaway and Josselyn 1992) and generally reaches a height of 0.5 - 1.5 m (Josselyn 1983). A dwarf form of *S. foliosa,* which grows to only 20 - 30 cm, occurs along the eastern shoreline of San Francisco Bay. The variation in height, as compared to the more robust form found throughout the Bay, was shown to be a result of a physiological response to environmental gradients, as the morphological dissimilarity observed in the field was not observed when both height forms were exposed to uniform, controlled environments (Cain and Harvey 1983).

Spartina foliosa is often a target species of salt marsh restorations but is frequently a difficult plant to establish. Slow to colonize new marsh areas (Josselyn 1983), it may take 4 - 8 years or longer before colonizing a mudflat across its elevational range (Josselyn 1988). Cordgrass establishment is often desired because it provides habitat for the once widely distributed California clapper rail. Due to the protection they provide from predators, cordgrass areas in tidal salt marshes support the highest densities of the California clapper rail (Josselyn 1983). Cordgrass areas are a favored nesting area of the rail, as well as other shorebirds (Josselyn 1983).

As developments and highways expand into wetlands, habitat losses continue. Laws such as the California Environmental Quality Act (CEQA) and Section 404 of the Clean Water Act require compensation, or mitigation, for lost or damaged wetlands. Although avoiding damage to wetlands is the preferred mitigation, restoration has become an increasingly popular form of compensation for wetland damage or loss. Compensatory mitigation for damages and losses of wetlands is an attempt to restore degraded wetlands and/or construct new ones. The basic objective of compensatory mitigation is to restore or create a habitat that provides the same values and functions as the site that is being destroyed. The mitigation should also reflect the values and functions of the region's ecosystems (PERL 1990). Primary ecological functions of San Francisco Bay wetlands include shoreline anchoring, nutrient retention, food chain support, wildlife habitats and fishery habitats (Josselyn, Zedler and Griswold 1990).

A primary question to be addressed when conducting or evaluating a wetland mitigation is whether the lost wetland values and functions are indeed being replaced. There has been concern that restoration attempts are not successfully replacing wetland values (Kusler and Kentula 1990). Some researchers debate whether any restoration site in the San Francisco Bay can be described as successful (Race 1985; but see Harvey & Josselyn 1986). Studies have shown that restored and constructed marshes are not completely functionally equivalent to natural marshes when comparing nutrient dynamics (Lindau and Hossner 1981; Craft, Broome, and Seneca, 1988a; Langis, Zalejko, and Zedler 1991), biomass and productivity (Zedler, Winfield, and Williams 1980; Langis, Zalejko, and Zedler 1991), and other parameters including waterbird utilization (Josselyn, Duffield, and Quammen 1987) and densities of epibenthic invertebrates (Zedler and Langis 1991). Many projects have been designed to restore wetlands and mitigate losses, but in most cases ecosystem functions have not been duplicated and endangered species have not been rescued from the threat of extinction (Zedler 1988). However, others believe restoration, even as a mitigation, is very valuable (Harvey and Josselyn 1986). Controversy exists concerning the success of restoration sites because few sites are monitored for parameters other than vegetation cover.

A number of studies conducted in the San Diego Bay were compiled to provide an overall evaluation of functional equivalency for four sections of a constructed wetland in relation to a natural marsh. Eleven parameters were compared, including nutrient dynamics, biomass and productivity, and epibenthic invertebrates. Zedler and Langis (1991) concluded that at 5 years of age, constructed marshes were, at best, less than 60 percent functionally equivalent to the natural marsh. Specifically, they found that, in the constructed marshes, total sediment inorganic nitrogen was only 45% of what was found in the natural marsh. Additionally, biomass of vascular plants was 42%, height of vascular plants was 65%, and epibenthic invertebrates were 36% of what was found in the natural marsh. The authors suggest that the slow development of the constructed marshes is a result of a number of relationships. Compared to the natural marsh, the substrate had little organic matter. With less soil organic matter, there was less energy and nitrogen for microbial processes and nitrogen fixation. With lower nitrogen inputs, plant growth is limited. With lower plant production and biomass, the detrital food chain may be impaired, as indicated by the lower abundance of epibenthic invertebrates found in the constructed marshes. Finally, with less food and shorter plants, the site may not yet be suitable as a habitat for the endangered clapper rail, the bird targeted for that site.

This study by Zedler and Langis (1991) directly addresses the frequently asked question of whether or not marsh functions are being replaced in restoration projects. The result of this study indicates that at 5 years of age, the restored San Diego marshes were not functionally equivalent to natural sites. However, is this true of most marshes at this age, or is this an isolated example? Replication of this study to additional sites and regions is necessary to answer this question. Comparable studies in the San Francisco Bay area that compare restored marshes to natural marshes would further indicate if and when functional equivalence is being reached by restored marshes, as well as indicate what percentage of natural marsh function the restored marshes are reaching.

A 1984 report prepared for the California Coastal Conservancy evaluated the State Coastal Conservancy's marsh restoration projects throughout California, half of which were from the San Francisco Bay area (Josselyn et al. 1993). The authors concluded that 59% of the projects evaluated met project goals in terms of either wetland functions or National Research Council (NRC) criteria. Questions developed by the NRC in 1992 as a means to judge project effectiveness include the following:

- To what extent is the restored ecosystem self-sustaining, and what are the maintenance requirements?
- If all natural ecosystem functions were not restored, have critical ecosystem functions and components been restored?
- Would another approach to restoration have produced the desirable results at lower cost?

The authors of the 1984 report concluded that the self-sustaining projects were those marshes with minimal or no hydrological controls. It is well known that the hydrological regime within a tidal marsh is a primary component in determining the characteristics of a marsh (Josselyn 1983; Mitsch and Gosselink 1993). Two basic approaches to restoring or creating wetlands have been used in the San Francisco Bay. The first approach involves breaching of the dikes between the marsh and the Bay to restore full tidal influx into the marsh. This technique allows for the restoration of natural tidal cycles to flow through the breached areas. The second approach is the use of culverts or other water control structures to restore reduced tidal influx. Culverts of a certain size, with or without flap gates, are placed at a certain elevation within the levee to control the amount of tidal influx that is allowed into the marsh. This method of restoration, which generally results in muted tidal fluctuation, has been used for a variety of reasons, including compensation for marsh plain subsidence, quick vegetation establishment, and flood control (Josselyn 1988). The use of culverts to control the tidal influx can result in hydrological regimes different from natural and dike-breached restored marshes. It is possible that different biotic and abiotic characteristics may result from the different hydrologies. Alterations of tidal circulation have an effect on the entire wetland ecosystem by changing the frequency of wetting and by altering salinities. In theory, the obstruction of tidal circulaton could either increase or decrease marsh inundation and salinity (Zedler, Winfield and Williams 1980). Changes in tidal flow could also affect nutrient conditions, since moisture influences decomposition and tidal circulation removes released nutrients from the system (Zedler, Winfield and Williams 1980). Thus, the differing lengths of time and ranges of tidal inundation resulting from the different approaches to restoring a tidal marsh may influence the soil characteristics within the marsh.

Both soil characteristics and tidal regime have been shown to affect vegetation composition and structure (Mendelssohn and Seneca 1980; Josselyn 1983; Zedler and Beare 1986; Gallagher 1974). Soil conditions have a major influence on vegetation growth and on the organisms that inhabit the rhizosphere of plants. Soil salinities control seed germination and seedling establishment in the coastal wetlands (Zedler and Beare 1986). Saline concentrations that are either too high or too low will alter vegetation composition by restricting growth of plants in the case of extreme hypersalinity or by allowing invasion by brackish or freshwater marsh species in the case of substantial salinity reductions (PERL 1990). The upper limit of *S. foliosa* is governed by high soil salinities (Mahall and Park 1976). Although the species in the San Francisco Bay grows best in salinities less than 15 ppt (Cain and Harvey 1983), it will continue to grow at reduced rates at salinities as high as 39.5 ppt (Mahall and Park 1976).

Nutrient dynamics and organic matter interact with chemical conditions within the sediment to control plant growth rates, and the presence and cycling of nutrients are important to the development and maintenance of both natural and restored marshes. Nitrogen has been shown to be of particular importance, as it has been identified as a limiting nutrient to *S. alterniflora*, a close relative of *S. foliosa* native to the east coast (Valiela and Teal 1974; Broome, Woodhouse and Seneca 1975), and to *S. foliosa* in southern California (Covin and Zedler 1988). When sample plots of *S. foliosa* were enriched with urea, a source of high nitrogen, measurements of total stem length, an estimate of aboveground biomass, were 13 - 60% greater than in unenriched plots (Covin and Zedler 1988).

Nitrogen levels and availability affect marsh plant productivity, standing biomass, diversity, and abundance of plant species (Valiela 1983).

Inadequate supplies of nitrogen are likely to affect wetland functions by altering the processes of primary production, decomposition, and food chain support (Langis, Zalejko and Zedler 1991). Organic matter is a major nitrogen storage pool (Haines et al. 1977), and soils with low organic matter will have low nitrogen fixation rates and therefore low supplies of nitrogen for the plants (PERL 1990). Recycing is believed to account for most of the nitrogen requirements of salt marsh vegetation (Haines et al. 1977). Mature marshes with deeper layers of organic matter recycle nitrogen better than young marshes with shallow layers (Morris and Bowden 1986). Studies have documented lower nitrogen concentrations in the soils of constructed wetlands when these were compared to natural sites (Lindau and Hossner 1981; Craft, Broome and Seneca 1988; Langis, Zalejko and Zedler 1991). NH_4^+ (ammonium) concentrations in a San Diego Bay constructed marsh were measured at 1.15 ppm while concentrations in an adjacent natural marsh measured 4.32 ppm. The aboveground biomass was believed to reflect these differences, as the constructed marsh had a dry biomass measurement of *S. foliosa* at 192 g/m^2, whereas the natural marsh had 453.42 g/m^2. The low nutrient levels in the constructed marsh were attributed to the poor organic matter pool within the marsh (Langis, Zalejko and Zedler 1991).

Tidal flushing is crucial in maintaining nutrient cycling and availability, as well as keeping salinities down. Aeration tends to decrease the impact of high salinity on cordgrass, and oxygen generally enhances nutrient uptake (Brenchly-Jackson 1992). Frequent tidal flux can bring nutrients and oxygen to the soil and leach out toxins. Growth of marsh plants can be reduced by inundation, which produces saturated, stagnant conditions as a result of sluggish tidal flow or impoundment (Mendelssohn & Seneca 1980; Howes et al. 1981). Saturated and stagnant conditions can also result in products within the soil that are toxic to plants (Brenchly-Jackson 1992). Tidal control structures have the potential to limit the amount of flushing within a restored marsh and create limitations to plant establishment and growth.

Restoration success is often judged by comparing the physical structure of the restored system to the natural system. This approach to assessing success, however, may result in habitats that are only structurally similar to natural systems but may lack functional attributes. Yet, a self-sustaining system must be able to function like the natural system, not just look like one. The structural and functional characteristics of coastal wetlands as they existed a century or more ago in California are unknown. Many of the disturbances to these once pristine habitats, such as watershed manipulation, are irreversible (Zedler 1984). Given such permanent changes to the ecosystem, restoration sites can be compared to those remaining natural sites with the least amount of disturbance. Additionally, model sites for comparison should be located in close proximity to the restored site to minimize differences in environmental gradients such as annual rainfall and water salinity.

The presence of natural ecosystem function in a restored habitat can be evaluated by testing the ecosystem for a number of functional parameters. Such parameters include sustainability, invasibility, productivity, and nutrient retention (Ewel 1987). A restored community must be capable of perpetuating itself, if conditions will allow this. The short term presence of vegetation does not ensure the long term success of the restoration.

Productivity is a particularly useful measure of community performance because it integrates many processes, including photosynthesis and nutrient availability (Ewel 1987). Not only should a successfully restored community should be as productive as the original, but it should also be able to retain nutrients as well as the original. A reconstructed community that loses greater amounts of nutrients than the original is not likely to be successful. In the long run, it will prove to be unsustainable because the chances of invasion by new species increases and thus its productivity will decline (Ewel 1987).

Given this information, measurements of productivity parameters would appear to be possible tools which agencies could use to assess the success of mitigation projects. Typically, vegetation is used as a measure of productivity. Vegetation parameters that are indicators of primary productivity, such as density, height and biomass, may also be indicators of soil nutrient and salinity status. Conversely, measurements of soil parameters such as salinity and nutrients may be indicators of potential productivity as well as other functional parameters, such as nitrogen fixation and adequate flushing.

In "A Manual for Assessing Restored and Natural Coastal Wetlands" by PERL (1990), specific functions have been identified as being essential for restoration success. These functions include provision of habitat for wetland-dependent species, support of food chains, transformation of nutrients, and maintenance of plant populations. To assess the success of restoration in attaining these functions, specific criteria have been identified as priority attributes to be monitored. These attributes include salinity, inorganic nitrogen in sediments, soil organic matter, and total stem length and height for cordgrass.

Study Questions

This research proposes to compare productivity and nutrient retention functions in natural, breached and culverted marshes by measuring vegetation and soil characteristics. Specifically, this project attempts to answer the following questions:

1. Are there differences in inorganic soil nitrogen and salinity between natural and breached or culverted restored tidal salt marshes in the San Francisco Bay?
2. Are there differences in *Spartina foliosa* productivity, as shown by measuring density, average stem height and total stem length between natural and breached or culverted restored tidal salt marshes in the San Francisco Bay?
3. To what extent do inorganic nutrients and salinity affect the productivity of *Spartina foliosa*?
4. To what extent do other factors affect variability in *Spartina foliosa* production?
5. Can nutrient soil testing act as an assessment parameter in restoration projects?
6. Are the results of the comparison between natural and restored marshes in the San Francisco Bay similar to the results of the San Diego Bay marsh studies by Zedler and Langis (1991)?

The results of this study should have implications beyond the marshes used in it. Soil conditions and resulting *Spartina foliosa* characteristics found in the marshes studied can be useful to managers of other restorations when they attempt to create the ideal conditions for *Spartina foliosa* establishment and growth. The results of this study should indicate whether or not soil parameter testing can act as an assessment parameter in *Spartina* marshes. Additionally, this study should provide an indication of which techniques used in restoration, dike breaching or the use of tide control structures, result in characteristics that allow a restored marsh to most closely resemble a natural marsh. It is hoped that these data regarding the development of restored salt marshes in the San Francisco Bay will be useful to regulatory agencies in determining if marsh restoration is an acceptable mitigation strategy.

Study Sites and Methods

In order to test differences between natural, breached and culverted marshes, two locations, with all three conditions represented, were found for this study (Figure 1). Marshes within each location were chosen in close proximity to one another to minimize variability across environmental gradients, such as Bay water salinity, temperature and rainfall so that comparisons would be feasible. The first location was Shoreline at Mountain View (Shoreline), located at the southern end of San Francisco Bay, approximately 45 miles south of the city of San Francisco. Three individual tidal marshes within Shoreline were studied for this project: Outer Charleston Slough, a natural marsh; Mountain View Tidal Marsh, a breached marsh; and Stevens Creek Tidal Marsh, a culverted marsh (Figure 2). The three marshes are within 1 mile (1.6 km) of one another. In 1973, the U.S. Army Corps of Engineers issued a permit requiring the city of Mountain View to restore 50 acres of vegetated salt marsh as mitigation for creating the 50 acre Shoreline Sailing Lake. Stevens Creek Tidal Marsh and Mountain View Tidal Marsh were set aside for restoration. Stevens Creek Tidal Marsh (SCTM) is a 29.5 acre site located on the eastern side of Shoreline and is connected to San Francisco Bay via Stevens Creek and Whisman Slough. In 1983, SCTM was re-opened to partial tidal action when two culverts were installed in the levee separating the Marsh from the adjacent Stevens Creek and the San Francisco Bay. Siltation and the formation of mudflats occurred

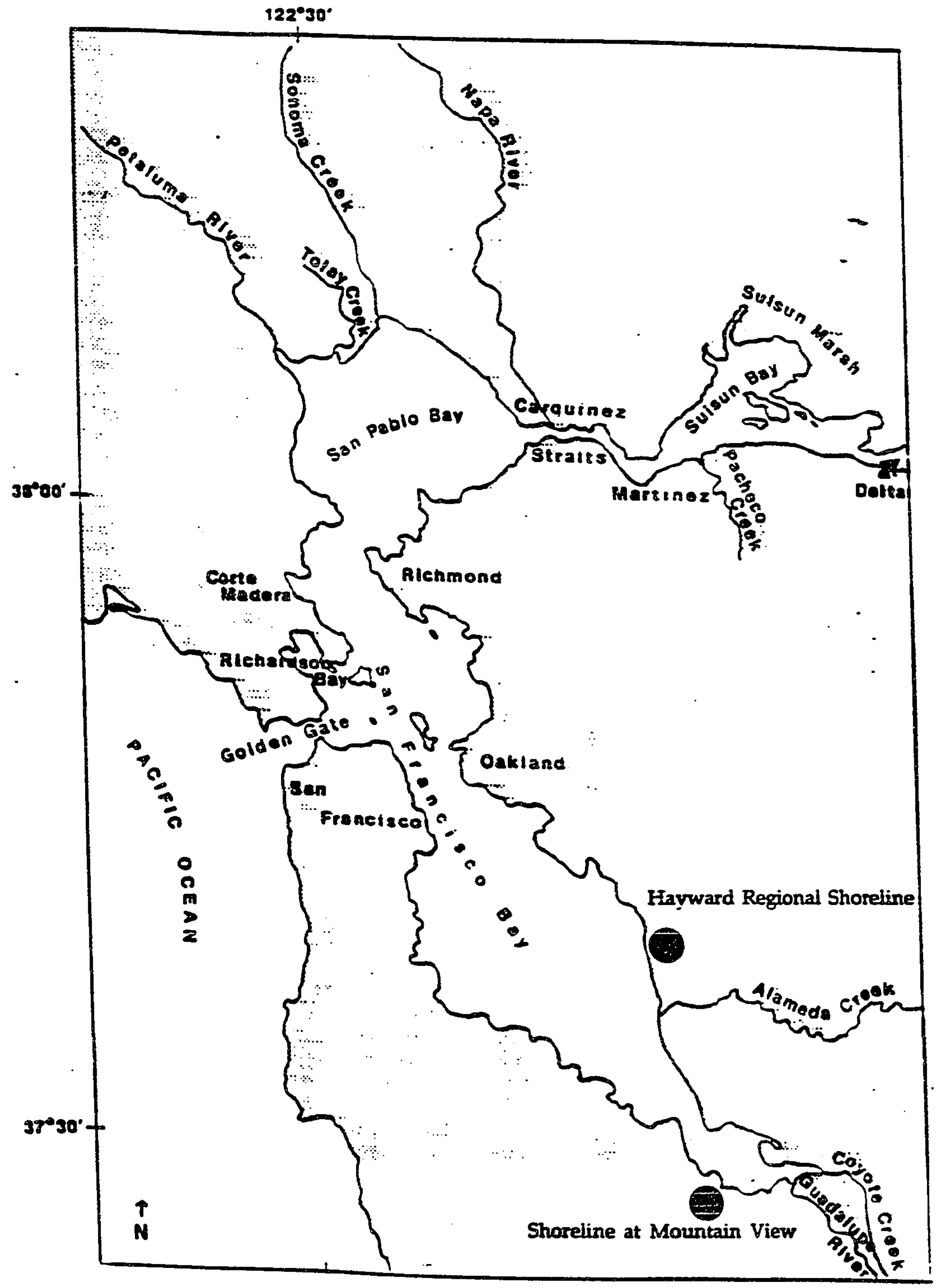

Figure 1. Study site locations within the San Francisco Bay region.
(Modified from Josselyn 1983)

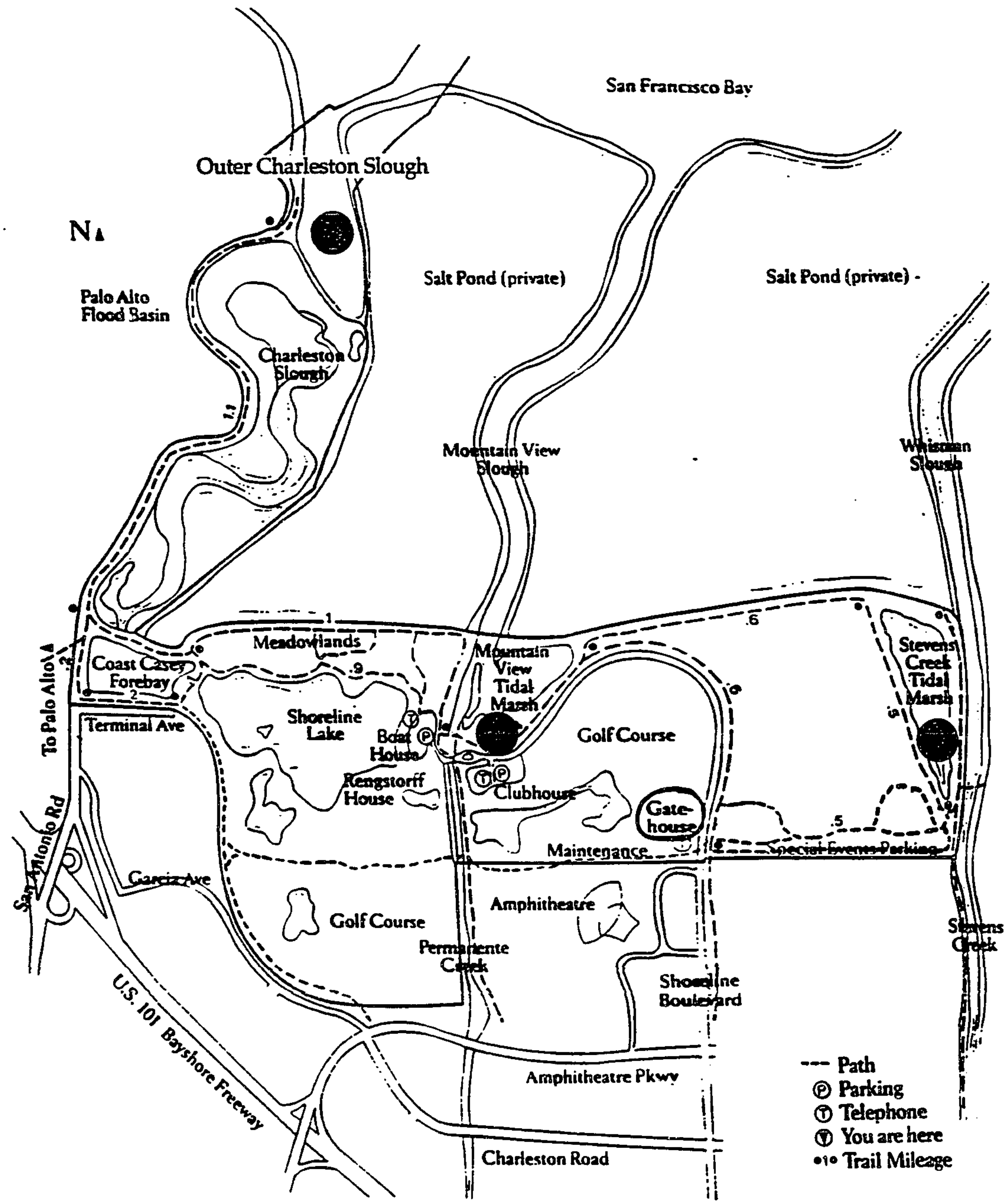

Figure 2. Shoreline at Mountain View site map. Site locations indicated by ●
(Map from Shoreline At Mountain View, City of Mountain View)

slowly, and in 1992, the Army Corps of Engineers issued a permit for the installation of two additional 48" culverts. In November 1992, the Marsh was opened to increased tidal action via the four culverts. Currently, tidal fluctuation in the Marsh is approximately 80 percent of full tidal action from San Francisco Bay, with maximum water levels at 4.0' (1.2 m) National Geodetic Vertical Datum of 1929 (NGVD) and minimum water levels at -2.5' (0.76 m) NGVD. Approximately 10 percent of the marsh is vegetated, and the remaining acres are developing mudflat and channels (City of Mountain View 1994).

Mountain View Tidal Marsh (MVTM) is a 20 acre site located in the center of Shoreline Park and is connected to San Francisco Bay via Mountain View Slough. In 1983, MVTM was re-opened to tidal action when the levee that separated the marsh from Mountain View Slough and the San Francisco Bay was breached in three locations. MVTM receives full tidal action from San Francisco Bay, with Mean Highest High Water (MHHW) estimated at 4.5' (1.4 m) NGVD and Mean Lowest Low Water (MLLW) estimated at -4.5' (-1.4 m) NGVD. Vegetation plantings took place in 1985 and 1987, and currently, the marsh is nearly fully vegetated with healthy pickleweed and cordgrass (M. Rogge, personal communication, February 1996).

The natural reference site chosen was Outer Charleston Slough, also located within Shoreline at Mountain View. This is a fully vegetated tidal marsh which is part of the Bay. Estimated tide levels for MHHW, MHW, MLW and MLLW are 4.5′ (1.4 m), 3.5′ (1.1 m), -3.5; (-1.1 m) and -4.5′ (-1.4 m), respectively (City of Mountain View 1992).

The second study location was along the Hayward Regional Shoreline (Figure 3). Hayward Regional Shoreline (Hayward) is located on the southeastern side of San Francisco Bay, approximately one mile north of the San Mateo Bridge. Sampled sites include one natural marsh (San Lorenzo Creek Marsh), one restoration site with culverts (Triangle Marsh), and two restoration sites with dike breaches (Cogswell Marsh). All marshes are within 1 1/2 miles (2.4 km) of each other.

The breached marshes are part of the 250 acre (101 hectare) Cogswell Marsh (Figure 4). Full tidal influx was restored to the Cogswell Marsh when the dikes were breached in 1980, connecting the marshes to San Francisco Bay. Tidal elevations in this area are 7.0′ (2.1 m) NGVD for the estimated highest tide and -5.5′ (-1.7 m) NGVD for the estimated lowest tide. MHHW is estimated at 4.5′ (1.4 m) NGVD and the MLLW is estimated at -3.0′ (0.9 m) NGVD. Cogswell Marsh is one of the handful of locations throughout San Francisco Bay in which the eastern smooth cordgrass species, *Spartina alterniflora*, can be found. Although numerous attempts have been made to eradicate this non-native species from the marsh, it continues to persist and spread. For this study, only sections of *S. foliosa* were selected for sampling within the nearly fully vegetated Cogswell Marsh.

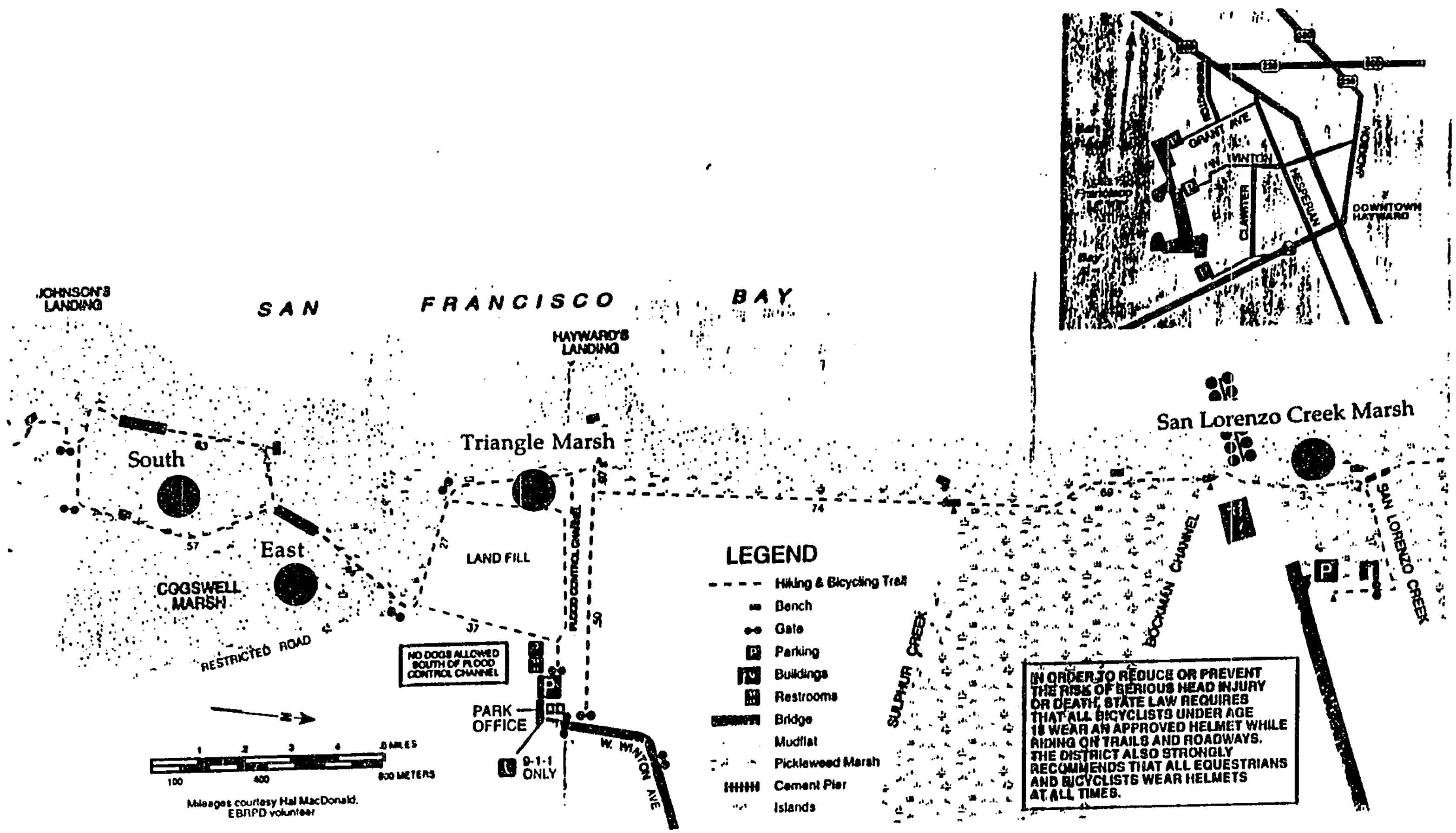

Figure 3. Hayward Regional Shoreline site map. Site locations indicated by ●
(Modified from East Bay Regional Park District 1994)

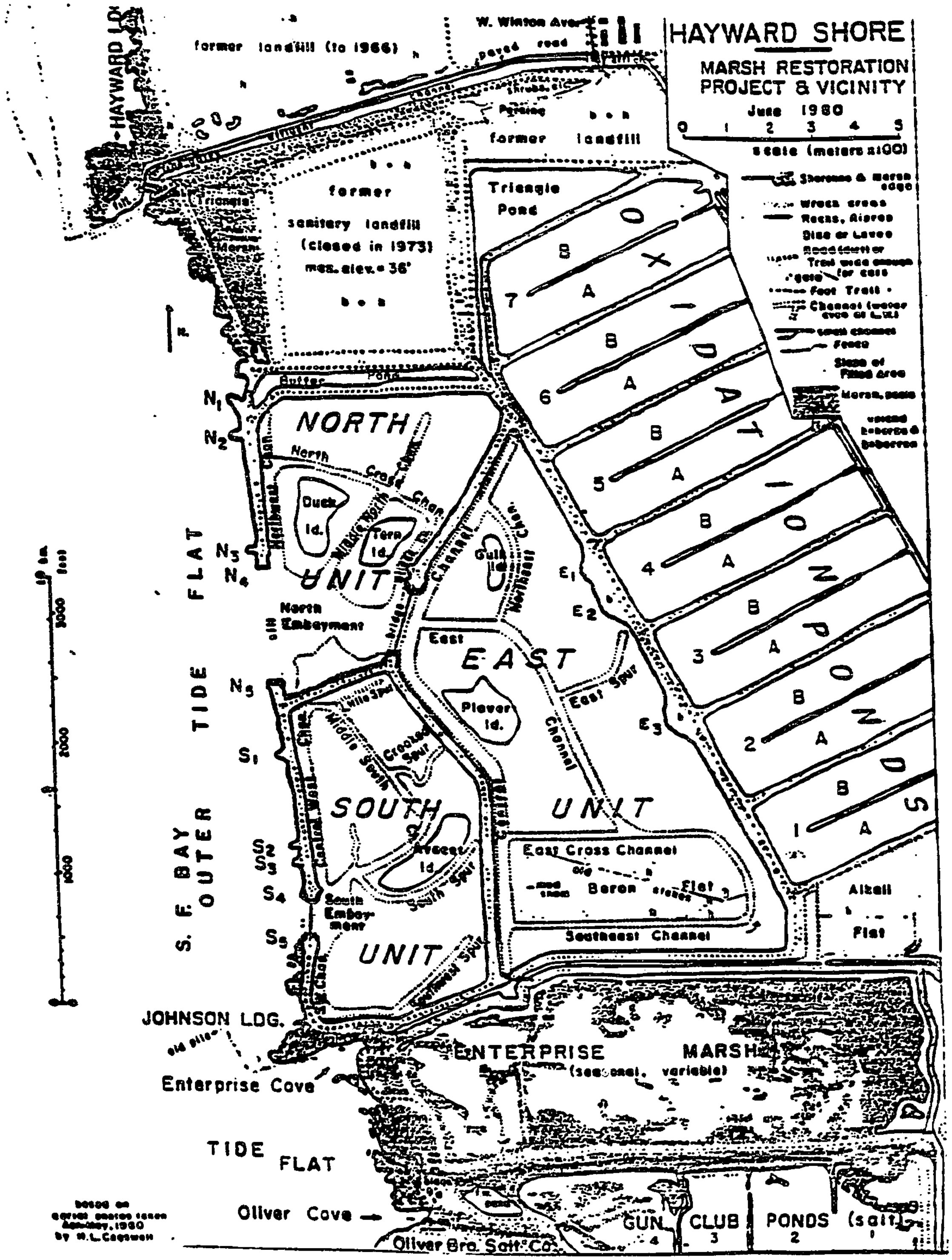

Figure 4. Cogswell Marsh Restoration and Triangle Marsh Restoration site map. (Map from Hayward Regional Shoreline, East Bay Regional Parks District)

The culverted marsh, Triangle Marsh, is a 7 acre (2.8 hectare) site located directly north of Cogswell Marsh, separated only by a buffer pond (Figure 4). Before the restoration, tidal circulation was restricted. In July and August 1990, a bulkwall and two 3'-diameter culverts with slide/flap gates were installed, connecting the marsh to the San Francisco Bay. In a 1992 monitoring report, 55% of the marsh plain was vegetated, of which more than 90% was pickleweed. There is no *S. foliosa* in this marsh currently. One flap gate remains closed and one gate fully open to provide a tide range of 0.25′ - 2.25′ (0.08 - 0.69 m) NGVD. This muted tidal flux is necessary to protect a neighboring landfill from erosion, as well as reduce the risk of flooding at a nearby street (Coats and Posternak 1988).

The natural reference site at the Hayward Regional Shoreline is located 1.4 miles (2.25 km) north of Triangle Marsh. It will be refered to as San Lorenzo Creek Marsh due to its proximity to San Lorenzo Creek. This is a fully vegetated tidal salt marsh that experiences the full tidal range of the area.

Sample Collection

For collection of vegetation and soil data, a stratified random sampling design was used. Transects were placed randomly within cordgrass areas and the location of sample plots along the transect were chosen with the use of a random number table. Data from 30 vegetation sample plots and 10 soil samples were collected from each marsh, with the exception of Triangle Marsh. *Spartina foliosa* does not grow within Triangle Marsh, so data was limited to the soil samples taken in that marsh.

A circular 0.25 m^2 sample plot size was used to measure the density of the cordgrass. Above-ground biomass was estimated by calculating the sum of *Spartina* heights to produce a measure called total stem length (tsl). The harvesting method of measuring biomass was avoided in this study since this technique is not recommended in areas of special concern, such as restored wetlands, because it may be too destructive (PERL 1990; Goldsmith 1991). Calculating the total stem length provides a non-destructive alternative to estimating biomass (Zedler and Nordby 1986). Cordgrass height was measured from the base to the tip of the tallest leaf. Vegetation data was collected between July and early September 1995.

Using a 2.5 cm core, sediment samples between 5 - 20 cm depth were taken from every third vegetation sample plot. Samples were placed in plastic bags and taken to a lab (Soil and Plant Laboratories, Santa Clara, CA) for analysis. Analysis included measurements of nitrogen (NO_3 and NH_4 by sodium chloride extraction), sodium (by saturation extraction method), and salinity. Salinity, or total salt content, was measured as EC_e, the electrical conductivity measured on the soil saturation extract in dS/m. This measurement was converted to parts per thousand (ppt) by the methods described by the California Fertilizer Association (1995). Soil data was also collected between July and early September 1995.

Statistical Analysis

The mean, standard deviation and variance were calculated for each vegetation parameter measured in each individual marsh. If the variance was greater than the mean, then the data was transformed using a logarithmic transformation to normalize the data. If 70% or more of the observations fell within the mean, plus or minus one standard deviation, and the variance was lower than the mean, then the data were considered to be normal (Fowler and Cohen 1990). A Student's t-test was applied to normal data and a Mann-Whitney U-test to non-normal data. Since the soil data had only 10 observations per parameter measured (with the exception of Triangle Marsh, which had only 5), the Mann-Whitney U-test was applied to determine differences between the medians.

Results

Shoreline at Mountain View - Vegetation

The stem density, average height of stems and the resulting total stem length (tsl) were all greatest in the natural marsh site, Outer Charleston Slough (OCS). Differences in stem density and tsl were not significant between Mountain View Tidal Marsh (MVTM) and OCS, although the average height of the cordgrass in MVTM was significantly shorter than the cordgrass in OCS (Table 1).

Table 1.--Vegetation comparison between Outer Charleston Slough and Mountain View Tidal Marsh

	n	Outer Charleston Slough	Mountain View Tidal Marsh	*P**
Stem Density (stalks/0.25m^2)	30	33.6 ± 7.9	31.1 ± 7.3	ns (0.208)
Avg. Stem Height (cm)	30	119.6 ± 9.5	113.5 ± 11.6	0.0236
Total Stem Length (m/0.25m^2)	30	40.1 ±9.5	35.6 ± 10.3	ns (0.057)

*Significance levels determined by Student's t-test; ns=not significant ($P>0.05$)

No significant difference was found between the average height of cordgrass in Stevens Creek Tidal Marsh (SCTM) and OCS (Table 2). The stem density and tsl, however, were significantly lower in SCTM than in OCS.

Table 2.--Vegetation comparison between Outer Charleston Slough and Stevens Creek Tidal Marsh

	n	Outer Charleston Slough	Stevens Creek Tidal Marsh	P*
Stem Density (stalks/0.25m^2)	30	33.6 ± 7.9	28.5 ± 5.6	0.00672
Avg. Stem Height (cm)	30	119.6 ± 9.5	119.5 ± 11.2	ns (0.9259)
Total Stem Length (m/0.25m^2)	30	40.1 ±9.5	34.0 ± 6.9	0.00797

*Significance levels determined by Student's t-test; ns=not significant (P>0.05)

The average stem height at SCTM was found to be significantly greater than the height at MVTM (Table 3). However, the differences in stem density and tsl were not significant between the two marshes.

Table 3.--Vegetation comparison between Mountain View Tidal Marsh and Stevens Creek Tidal Marsh

	n	Mountain View Tidal Marsh	Stevens Creek Tidal Marsh	P*
Stem Density (stalks/0.25m^2)	30	31.1 ± 7.3	28.5 ± 5.6	ns (0.1708)
Avg. Stem Height (cm)	30	113.5 ± 11.6	119.5 ± 11.2	0.04188
Total Stem Length (m/0.25m^2)	30	35.6 ± 10.3	34.0 ± 6.9	ns (0.69)

*Significance levels determined by Student's t-test; ns=not significant (P>0.05)

Shoreline at Mountain View - Soils

MVTM soil was not found to be significantly different from OCS soil for the parameters measured, with the exception of NH_4, for which MVTM was higher (Table 4). SCTM soil was significantly different in all soil parameters measured when compared to OCS (Table 5) and MVTM (Table 6).

Table 4.--Soil parameter comparison between Outer Charleston Slough and Mountain View Tidal Marsh

	Outer Charleston Slough	Mountain View Tidal Marsh	*P**
NO_3 (ppm)	1.6 ± 1.1	1.4 ± 0.7	ns
NH_4 (ppm)	13 ± 2.5	16.5 ± 6.3	<.05
Na (ppt)	9.5 ± 1.4	10.1 ± 2.7	ns
Salinity (ppt)	30.7 ± 4.0	30.1 ± 6.5	ns

*Significance levels determined by the Mann-Whitney test; ns=not significant (P>0.05).

Table 5.--Soil parameter comparison between Outer Charleston Slough and Stevens Creek Tidal Marsh

	Outer Charelston Slough	Stevens Creek Tidal Marsh	*P**
NO_3 (ppm)	1.6 ± 1.1	2.9 ± 2.0	<.05
NH_4 (ppm)	13 ± 2.5	11.9 ± 1.7	<.05
Na (ppt)	9.5 ± 1.4	5.9 ± 1.3	<.05
Salinity (ppt)	30.7 ± 4.0	21.1 ± 4.6	<.05

*Significance levels determined by the Mann-Whitney test; ns=not significant (P>0.05).

Table 6.--Soil parameter comparison between Mountain View Tidal Marsh and Stevens Creek Tidal Marsh

	Mountain View Tidal Marsh	Stevens Creek Tidal Marsh	*P**
NO_3 (ppm)	1.4 ± 0.7	2.9 ± 2.0	<.05
NH_4 (ppm)	16.5 ± 6.3	11.9 ± 1.7	<.05
Na (ppt)	10.1 ± 2.7	5.9 ± 1.3	<.05
Salinity (ppt)	30.1 ± 6.5	21.1 ± 4.6	<.05

*Significance levels determined by the Mann-Whitney test; ns=not significant (P>0.05).

Hayward - Vegetation

Vegetation data are not available for Triangle Marsh, the culverted marsh, since the few clumps of cordgrass present in the marsh were *S. alterniflora*. Although the two units of the Cogswell Marsh were both breached and are considered to be part of the same marsh, data for the two units sampled (south and east) were not combined because significant differences were identified between them (Table 7).

Table 7.--Vegetation comparison between Cogswell Marsh South Unit and Cogswell Marsh East Unit

	n	Cogswell Marsh - South	Cogswell Marsh - East	*P**
Stem Density (stalks/0.25m^2)	30	42.3 ± 10.1	40.7 ± 10.7	ns (0.485)
Avg. Stem Height (cm)	30	82.9 ± 8.5	73.0 ± 7.9	0.00001
Total Stem Length (m/0.25m^2)	30	34.8 ± 7.5	29.2 ± 6.4	0.0039

*Significance levels determined by Student's t-test; ns=not significant ($P>0.05$)

The stem density, average height of stems and resulting total stem length (tsl) were greatest in the natural marsh located at the end of San Lorenzo Creek. Although stem densities were found to be similar in all three marshes containing cordgrass, average height and tsl were found to be significantly different among the three. Average stem heights were significantly shorter and tsl significantly less in Cogswell Marsh-South (CMS) and Cogswell Marsh-East (CME) than in the San Lorenzo Creek Marsh (Tables 8 and 9).

Table 8.--Vegetation comparison between San Lorenzo Creek Marsh and Cogswell Marsh South Unit

	n	San Lorenzo Creek Marsh	Cogswell Marsh - South	P*
Stem Density (stalks/0.25m^2)	30	44.7 ± 11.1	42.3 ± 10.1	ns(0.437)
Avg. Stem Height (cm)	30	97.6 ± 6.9	82.9 ± 8.5	2.45×10^{-9}
Total Stem Length (m/0.25m^2)	30	43.3 ± 10.1	34.8 ± 7.5	0.0006

*Significance levels determined by Student's t-test; ns=not significant (P>0.05)

Table 9.--Vegetation comparison between San Lorenzo Creek Marsh and Cogswell Marsh East Unit

	n	San Lorenzo Creek Marsh	Cogswell Marsh - East	P*
Stem Density (stalks/0.25m^2)	30	44.7 ± 11.1	40.7 ± 10.7	ns (0.162)
Avg. Stem Height (cm)	30	97.6 ± 6.9	73.0 ± 7.9	1.44×10^{-17}
Total Stem Length (m/0.25m^2)	30	43.3 ± 10.1	29.2 ± 6.4	2.19×10^{-8}

*Significance levels determined by Student's t-test; ns=not significant (P>0.05)

Hayward - Soils

Soil data for CME and CMS showed significant differences in two of the four parameters studied (Table 10). CMS had a significant difference when compared to San Lorenzo Creek Marsh (SLCM) in the parameters studied, with the exception of NO_3 (Table 11). No significant difference was observed between CME and SLCM in any of the four parameters measured (Table 12).

Triangle Marsh also was found to have soil parameters similar to those of SLCM, with the exception of NH_4 (Table 13).

Table 10.--Soil parameter comparison between Cogswell Marsh East Unit and Cogswell Marsh South Unit

	Cogswell Marsh - East	Cogswell Marsh - South	*P**
NO_3 (ppm)	2.6 ± 2.1	4.1 ± 3.7	ns
NH_4 (ppm)	15.2 ± 7.9	19.2 ± 5.2	<.05
Na (ppt)	9.5 ± 2.8	12.9 ± 3.1	<.05
Salinity (ppt)	31.7 ± 8.2	37.1 ± 6.9	ns

*Significance levels determined by the Mann-Whitney test; ns=not significant (P>0.05).

Table 11.--Soil parameter comparison between San Lorenzo Creek Marsh and Cogswell Marsh South Unit

	San Lorenzo Creek Marsh	Cogswell Marsh - South	*P**
NO_3 (ppm)	2.2 ± 1.6	4.1 ± 3.7	ns
NH_4 (ppm)	10.5 ± 2.9	19.2 ± 5.2	<.05
Na (ppt)	8.9 ± 1.5	12.9 ± 3.1	<.05
Salinity (ppt)	27.7 ± 5.3	37.1 ± 6.9	<.05

*Significance levels determined by the Mann-Whitney test; ns=not significant (P>0.05).

Table 12.--Soil parameter comparison between San Lorenzo Creek Marsh and Cogswell Marsh East Unit

	San Lorenzo Creek Marsh	Cogswell Marsh - East	*P**
NO_3 (ppm)	2.2 ± 1.6	2.6 ± 2.1	ns
NH_4 (ppm)	10.5 ± 2.9	15.2 ± 7.9	ns
Na (ppt)	8.9 ± 1.5	9.5 ± 2.8	ns
Salinity (ppt)	27.7 ± 5.3	31.7 ± 8.2	ns

*Significance levels determined by the Mann-Whitney test; ns=not significant (P>0.05).

Table 13.--Soil parameter comparison between San Lorenzo Creek Marsh and Triangle Marsh

	San Lorenzo Creek Marsh	Triangle Marsh	*P**
NO_3 (ppm)	2.2 ± 1.6	1.4 ± 0.9	ns
NH_4 (ppm)	10.5 ± 2.9	14.6 ± 1.5	<.05
Na (ppt)	8.9 ± 1.5	9.4 ± 0.8	ns
Salinity (ppt)	27.7 ± 5.3	32.3 ± 1.9	ns

*Significance levels determined by the Mann-Whitney test; ns=not significant (P>0.05).

Discussion

Restored vs. Natural Marshes

The results of this study are indicative of the variability between marshes, and the variety of parameters that can influence the vegetation structure and function within a tidal marsh. All the restored marshes studied were found to be significantly different from their natural references in either soil or vegetation characteristics. Table 14 shows the number of parameters for which there was no statistically significant difference between the restored and natural sites.

Table 14.--The number of parameters in which the restored marshes showed no significant difference to their natural reference sites, based on statistical analysis

Marsh Name	Number of Parameters
Mountain View Tidal Marsh (breached)	5 of 7
Stevens Creek Tidal Marsh (culverted)	1 of 7
Cogswell Marsh South Unit (breached)	2 of 7
Cogswell Marsh East Unit (breached)	5 of 7
Triangle Marsh (culverted)	3 of 7

Two breached marshes, MVTM at Shoreline and CME at Hayward, showed the greatest similarity to their natural references as there was no significant difference in 5 of the 7 parameters measured. SCTM at Shoreline demonstrated the least similarity by showing no significant difference in only 1 of 7 parameters measured. At both Hayward and Shoreline sites, the natural marshes showed the greatest average stem density, average stem height, and total stem length (Figures 5 and 6). Sediment characteristics showed a variety of differences between the restored marshes and the natural sites (Figures 7 and 8), with the exception of CME which was similar to the natural site in all 4 sediment parameters.

When their similarities were compared to Outer Charleston Slough (OCS), the natural site, the two restored marshes at Shoreline showed the most drastic differences (Table 15).

Table 15.--Percent equivalency for the restored marshes at Shoreline at Mountain View in relation to the natural reference site at Outer Charleston Slough, based on sample means.

	Mountain View Tidal Marsh	Stevens Creek Tidal Marsh
Avg. Stem Density	93*	85
Avg. Stem Height	95	99*
Total Stem Length	89*	85
Sediment NO_3	88*	181
Sediment NH_4	127	92
Sediment Na	107*	62
Sediment Salinity	98*	69

*Differences not significant, based on statistical analysis.

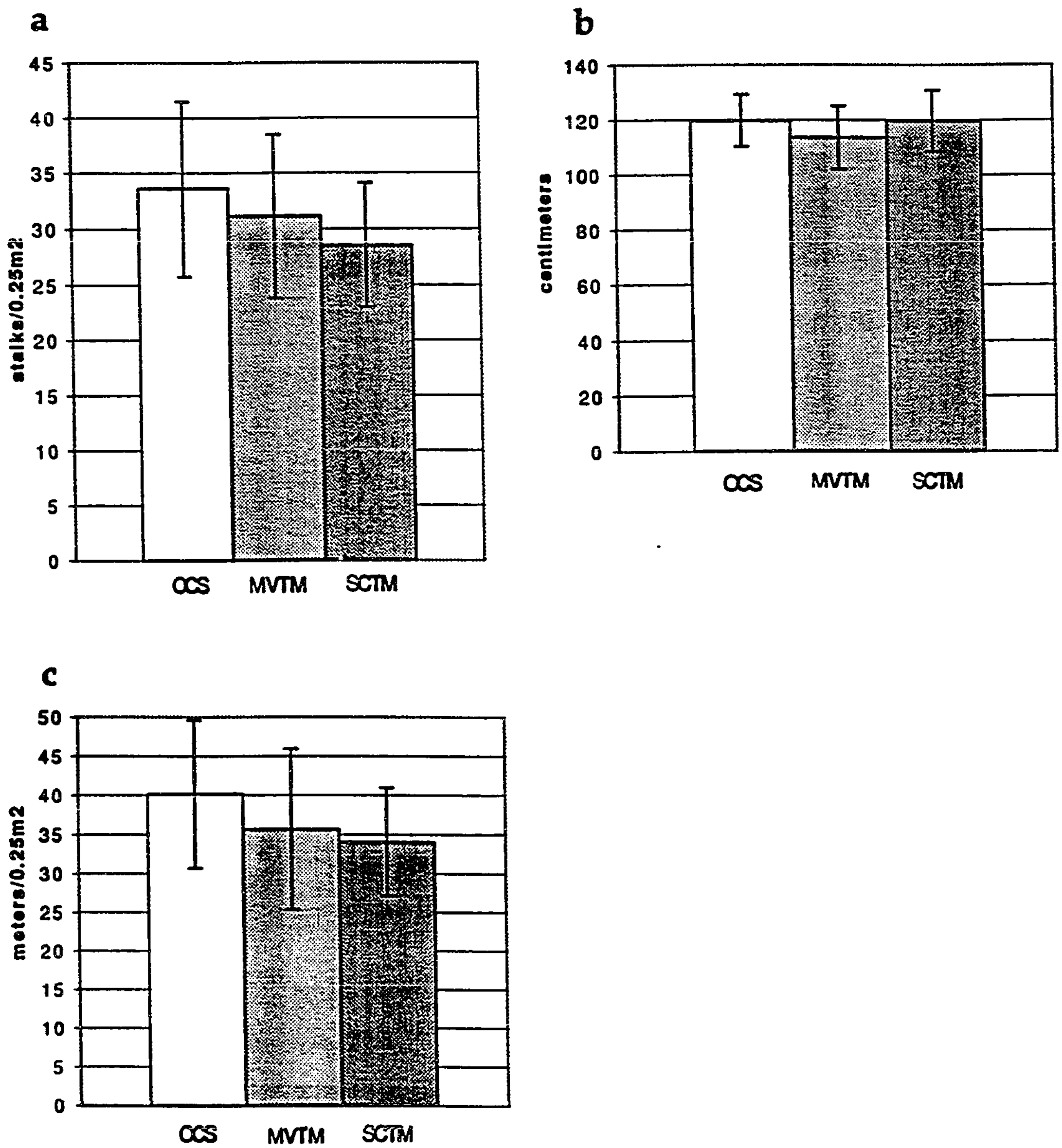

Figure 5. Comparison of vegetation characteristics between Outer Charleston Slough (natural), Mountain View Tidal Marsh (breached), and Stevens Creek Tidal Marsh (culverted).
(a) Stem Density (stalks/0.25m^2) - OCS (33.6 $\pm$ 7.9); MVTM (31.1 $\pm$ 7.3); SCTM (28.5 $\pm$ 5.6).
(b) Average Cordgrass Height (cm) - OCS (119.6 $\pm$ 9.5); MVTM (113.5 $\pm$ 11.6); SCTM (119.5 $\pm$ 11.2).
(c) Total Stem Length (m/0.25m^2) - OCS (40.1 $\pm$9.5); MVTM (35.6 $\pm$ 10.3); SCTM (34.0 $\pm$ 6.9).

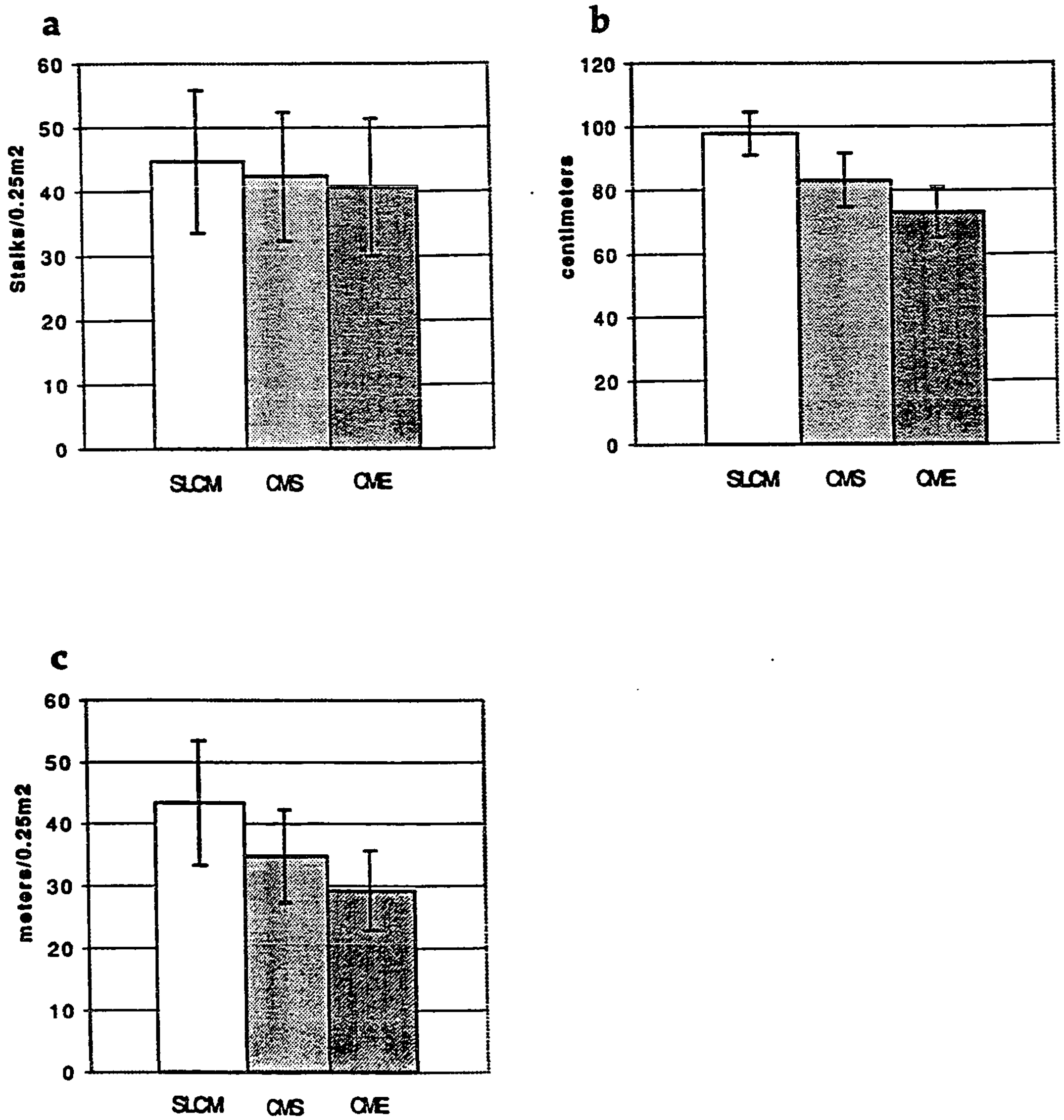

Figure 6. Comparison of vegetation characteristics between San Lorenzo Creek Marsh (natural), Cogswell Marsh-East (breached), and Cogswell Marsh-South (breached).
(a) Stem Density (stalks/0.25m^2) - SLCM (44.7 ± 11.1); CMS (42.3 ± 10.1); CME (40.7 ± 10.7).
(b) Average Cordgrass Height (cm) - SLCM (97.6 ± 6.9); CMS (82.9 ± 8.5); CME (73.0 ± 7.9).
(c) Total Stem Length (m/0.25m^2) - SLCM (43.3 ± 10.1); CMS (34.8 ± 7.5); CME (29.2 ± 6.4).

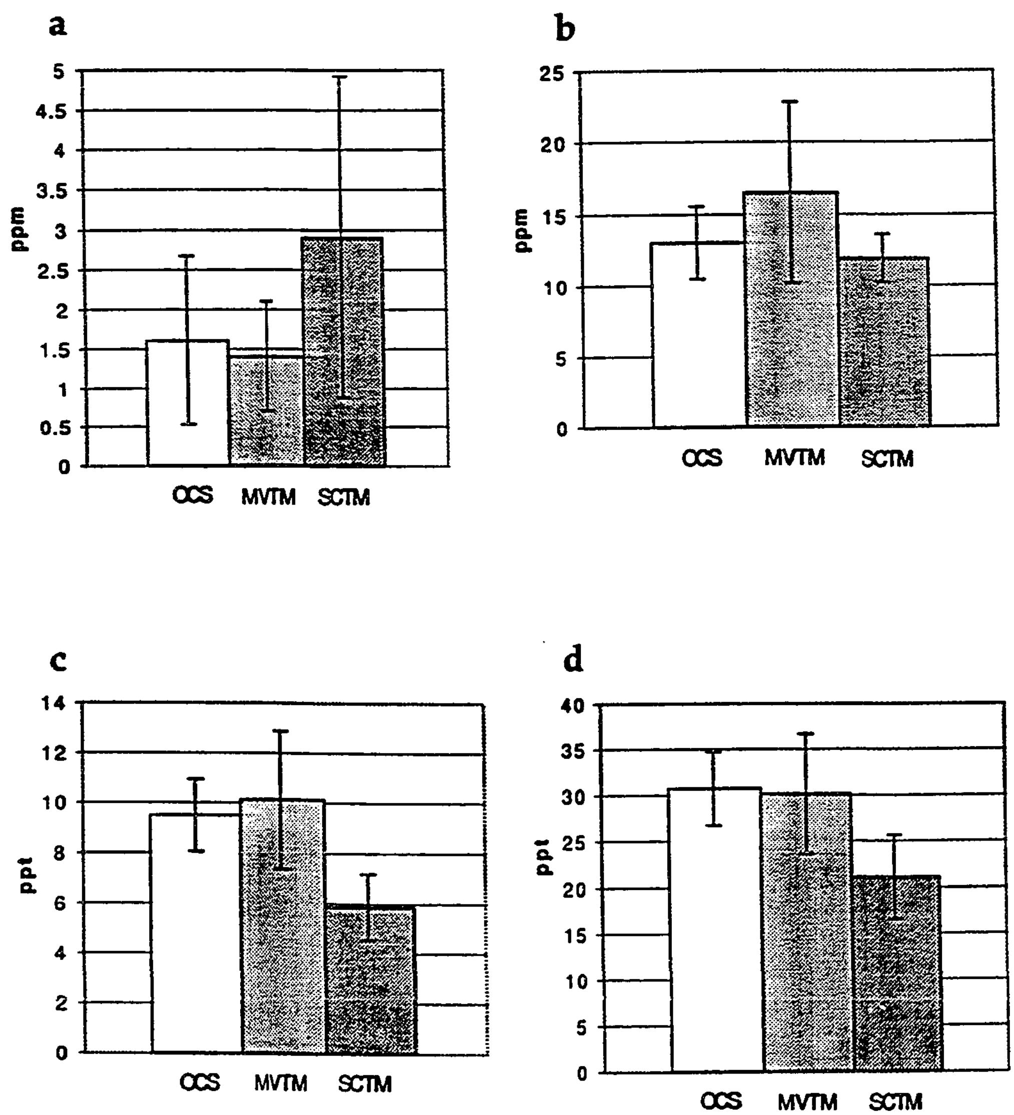

Figure 7. Comparison of sediment characteristics between Outer Charleston Slough (natural), Mountain View Tidal Marsh (breached), and Stevens Creek Tidal Marsh (culverted).
(a) NO_3 (ppm) - OCS (1.6 ± 1.1); MVTM (1.4 ± 0.7); SCTM (2.9 ± 2.0)
(b) NH_4 (ppm) - OCS (13.0 ± 2.5); MVTM (16.5 ± 6.3); SCTM (11.9 ± 1.7)
(c) Na (ppt) - OCS (9.5 ± 1.4); MVTM (10.1 ± 2.7); SCTM (5.9 ± 1.3)
(d) Salinity (ppt) - OCS (30.7 ± 4.0); MVTM (30.1 ± 6.5); SCTM (21.1 ± 4.6)

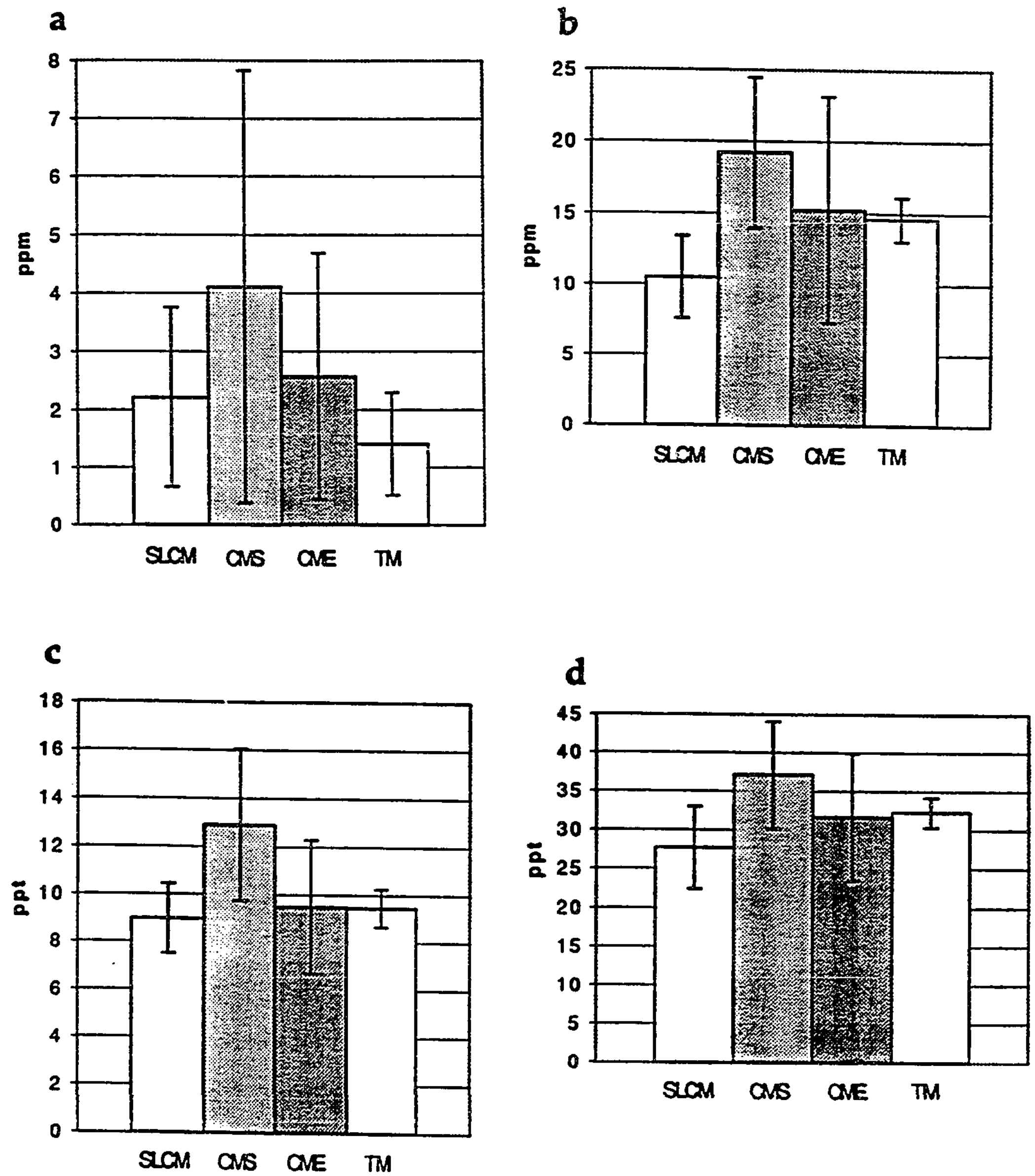

Figure 8. Comparison of sediment characteristics between San Lorenzo Creek Marsh (natural), Cogswell Marsh-South (breached), Cogswell Marsh-East (breached), and Triangle Marsh (culverted).
(a) NO_3 (ppm) - SLCM (2.2 ± 1.6); CMS (4.1 ± 3.7); CME (2.6 ± 2.1); TM (1.4 ± 0.9)
(b) NH_4 (ppm) - SLCM (10.5 ± 2.9); CMS (19.2 ± 5.2); CME (15.2 ± 7.9); TM (14.6 ± 1.5)
(c) Na (ppt) - SLCM (8.9 ± 1.5); CMS (12.9 ± 3.1); CME (9.5 ± 2.8); TM (9.4 + 0.8)
(d) Salinity (ppt) - SLCM (27.7 ± 5.3); CMS (37.1 ± 6.9); CME (31.7 ± 8.2); TM (32.3 ± 1.9)

Although two of the seven parameters measured at MVTM were shown to have statistically significant differences from those measured at OCS, a comparison of the means indicates that statistical significance in these cases may not be practical. The first of these parameters is average stem height. The average height at MVTM, 113.47 cm, was 95% of the average height at OCS, 119.63 cm. Although statistical analysis showed a significant difference between the two marshes in this parameter, the difference between the means lack practical significance. Total stem length, which combines stem length and density, may be a more important measure. The other parameter in which a significant difference was found was in the sediment NH_4 levels. At 16.5 ppm, MVTM had NH_4 levels at 127% of the levels found at OCS. Given that nitrogen is a potential limiting nutrient within salt marshes, this greater amount of NH_4 may be beneficial to the plant growth within this marsh.

At SCTM, six of the seven parameters measured were shown to be significantly different from OCS. The cordgrass stalks at SCTM were similar in height to those at OCS, but stem density and tsl were significantly less, both of which averaged only 85% of the measurements at OCS. All four sediment parameters at SCTM were found to be significantly different from those at OCS. At 69% of the salinity at OCS, this difference in total dissolved salts is probably significant enough to affect vegetation growth at SCTM. However, when the means of both NO_3 and NH_4 are compared, the differences may be too slight to affect vegetation growth. Although the percent NO_3 at SCTM was 181% of the NO_3 levels found at OCS, the difference between the means was only 1.3 ppm. Additionally, although significantly different, the NH_4 levels at SCTM were found to be 92% of the NH_4 levels at OCS, with the difference between the means being only 1.1 ppm.

At Hayward Shoreline, CME most closely resembled SLCM, as 5 of the 7 parameters measured at CME were not significantly different from those of SLCM. Differences were found in average stem height and tsl, with the measurements at CME being 75% and 67% of those at SLCM, respectively (Table 16).

Table 16: Percent equivalency for the restored marshes at Hayward Shoreline in relation to the natural reference site at San Lorenzo Creek, based on sample means.

	Cogswell Marsh South Unit	Cogswell Marsh East Unit	Triangle Marsh
Avg. Stem Density	95*	91*	....
Avg. Stem Height	85	75	....
Total Stem Length	80	67	....
Sediment NO_3	186*	116*	63*
Sediment NH_4	183	145*	139
Sediment Na	144	106*	106*
Sediment Salinity	134	114*	117*

*Differences not significant, based on statistical analysis.

Although still significantly less than at SLCM, height and tsl at CMS were closer to the measurements at SLCM than at CME, with average stem height and tsl being 85% and 80% of those at SLCM, respectively.

At Triangle Marsh (TM), three of the four sediment parameters measured were not found to be significantly different from SLCM. Despite this statistical finding, the average NO_3 level at TM was found to be 63% of the average measured at SLCM. However, a comparison of the means identifies a difference (0.8 ppm) that may be too slight to affect plant growth.

Compared to the results of the study by Zedler and Langis (1991) conducted in San Diego Bay, the restored marshes at Shoreline and Hayward were generally closer to resembling their natural reference sites. The height of vascular plants at the constructed marsh in San Diego Bay was calculated to be 65% functionally equivalent to the natural reference marsh. In this study, height comparisons ranged from 75 - 99%. For SCTM, at 3 years after enhancement of tidal flushing, the equivalency was 99%. In the San Diego Bay study, equivalency in biomass of vascular plants was calculated to be 42%. In this study, equivalency calculations for tsl, a non-destructive estimate of biomass, ranged from 67 - 89%. For SCTM, the equivalency was 85%. Sediment inorganic nitrogen levels at the constructed marsh in San Diego Bay were calculated to be 45% of the levels found at the natural reference site. In this study, NH_4 comparisons ranged from 92 - 183%, and NO_3 from 63 - 186%. For SCTM, the equivalency was 92% for NH_4 and 181% for NO_3. At three years since enhancement, SCTM is closer to resembling a natural reference marsh in both plant and soil characteristics than the constructed marsh studied by Zedler and Langis in San Diego Bay.

Variability in Parameters

The results from the marshes tested for this study indicate that variability in parameters do not allow a simple correlation between inorganic nitrogen and plant growth. There was heterogeneity both within and between marshes, and in all marshes studied, there was variability in factors contributing to the density, average height, and tsl of the cordgrass. Plant growth is influenced by numerous other factors including salinity, nitrogen concentrations, marsh age, and tidal flushing.

Salinity. In the San Francisco Bay, numerous studies have tested the tolerance range of *S. foliosa* to various sediment salinities. Cain and Harvey (1983) tested *S. foliosa* growth at salinity concentrations of 0.4 osmole/kg H_2O (11.7 ppt), 0.8 osmole/kg H_2O (23.4 ppt) and 1.2 osmole/kg H_2O (35.1 ppt). Of the three salinities tested, *S. foliosa* growth was greatest at 11.7 ppt, reaching a height of 61 cm. At 23.4 ppt salinity, cordgrass height averaged 54 cm, at 35.1 ppt salinity, 47 cm. *S. foliosa* growth was believed to become reduced somewhere between 23.4 and 35.1 ppt. In an earlier study, Mahall and Park (1976) measured the mean dry weights of *S. foliosa* grown in nutrient solutions of various salinities. Maximum dry weight was found at 0.58

osmole/kg H_2O (16.97 ppt) and dry weight decreased by ~42% when salinities were increased to 0.78 osmole/kg H_2O (22.82 ppt). At higher salinities, there was a steady decline of about 10% in plant height for every 0.2 osmole/kg H_2O (5.85 ppt) increase in salinity. At 1.35 osmole/kg H_2O (39.49 ppt) growth still occurred, but at a 66% decrease from the maximum.

At a 21.06 ppt level of salinity, SCTM at Shoreline falls below the 23.4 to 35.1 ppt salinity range identified by Cain and Harvey (1983) where the *S. foliosa* growth rate became reduced. Sediment salinity at the natural marsh, OCS, was 30.69 ppt. Although potential salinity levels were significantly greater in OCS than SCTM and measured NH_4 levels were found to be significantly lower in SCTM than OCS, no significant difference was found between the average stem heights of the two marshes. This similarity in stem heights, given the lower NH_4 levels in SCTM, can probably be explained by the significantly lower salinity levels found at SCTM. Linthurst and Seneca (1981) have shown that at low salinity (15 ppt), *S. alterniflora* removed more nutrients from substrate than at 45 ppt in the same time period. The low salinity conditions at SCTM may be allowing the plants to have increased nutrient uptake, resulting in increased plant height.

At Hayward, all marsh salinities fall within the 23.4 - 35.1 ppt salinity range identified by Cain and Harvey (1983) where the *S. foliosa* growth rate became reduced. Based on salinity levels alone, one would expect shorter cordgrass in the marshes with higher salinity. However, the results show that this is not the case. CMS had relatively high salinity levels compared to CME, but the average cordgrass height was taller in the southern unit. An explanation for this greater productivity may be the significantly higher NH_4 levels in CMS than in CME.

Nitrogen. Many researchers have investigated the effects of nitrogen on the growth of *S. alterniflora* (Sullivan and Daiber 1974; Valiela and Teal 1974; Broome, Woodhouse and Seneca 1975; Gallagher 1975; Patrick and Delaune 1976; Mendelssohn 1979). The results of their experiments suggest that nitrogen is a limiting growth factor in the short form of *S. alterniflora* marshes. Experimental fertilization with nitrogen on *S. foliosa* in southern California marshes resulted in plants with greater density and biomass (Covin and Zedler 1988; Gibson, Zedler and Langis 1994), suggesting that nitrogen is a limiting growth factor for *S. foliosa* also. In comparing a constructed marsh to a natural marsh, Langis, Zalejko and Zedler (1991) found the natural marsh to contain 3.17 ppm more NH_4^+ and more than twice the biomass than in the constructed marsh.

Although significantly greater amounts of nutrients, particularly nitrogen, were found in CMS than in the natural SLCM, the average plant heights were significantly shorter. This difference may again be explained by the significantly greater substrate salinity. Researchers have hypothesized that high nutrient concentrations with minimal growth could be the result of numerous physiological responses of *S. alterniflora* to increasing salinities.

One of these responses could be a NH_4^+-Na^+ competition affecting nitrogen uptake and/or metabolism by *S. alterniflora.* As salinity increases, considerably more nitrogen would be necessary to compensate for this competition effect (Haines and Dunn 1976; Linthurst and Seneca 1981). Other researchers have found that a significant negative correlation between interstitial water salinity and NH_4 suggested a possible negative interaction between these two variables (Smart and Barko 1980).

At MVTM at Shoreline a different scenario develops. When the soils between OCS and MVTM were compared, no significant differences were found in the parameters measured, except for NH_4 which was found to be higher at MVTM. The stem density and total stem length were not significantly different between these two marshes, but the average stem height was higher in OCS. Although this contradicts the idea that an increase in nitrogen will provide increased productivity, similar results were found in a North Carolina salt marsh. Mendelssohn (1979) measured higher concentrations of NH_4 in the interstitial waters of a short *Spartina* marsh than in a nearby tall *Spartina* marsh. He suggested that the nitrogen deficiency seen in the short form may be a secondary response to some factor or factors which prevent the uptake and/or assimilation of high concentrations of ammonium present in the interstitial water.

Tidal Flushing and Marsh Age. Additional factors that may influence *Spartina* productivity include tidal inundation, marsh plain elevation, substrate redox potential (soil drainage), soil aeration, ion toxicity, and other nutrient deficiencies. Mendelssohn and Seneca (1980) observed that 70% of variation in *S. alterniflora* plant height was explained by differences in redox potential and experimentally found that the growth of *S. alterniflora* was significantly impaired in stagnant water. Other researchers have also indicated that plant height is positively related to inundation time (Stalter and Batson 1969; Gallagher 1974). Linthurst and Seneca (1981) found that, in combination with high nitrogen levels, aeration of the soils surrounding the roots was more effective in overcoming the detrimental effects of high salinity than high nitrogen alone. They also found that aeration alone also had a beneficial effect on plant growth at all of the salinities that they tested. One study found that variation in *S. alterniflora* biomass was closely correlated with sediment oxidation (Howes, Dacey and Goehringer 1986), while others have found that plant nitrogen uptake is highly correlated with oxygen concentrations around roots (Morris and Dacey 1984).

Perhaps one or more of these factors can explain the differences found in vegetation characteristics between CME and SLCM. Although differences in the measured soil parameters between the two marshes were found not to be significant, there were significant differences found between the plant height and resulting total stem length. There may be differences in tidal flushing between the two marshes as SLCM is open completely to the San Francisco Bay, whereas CME is open to the Bay only through the dike breached area. Whether this difference in tidal flushing is significant and whether differences in parameters such as soil aeration, redox potential and toxin accumulation exist are areas of further study.

Although Triangle Marsh (TM) soil parameters are similar to SLCM soils, there is no significant growth of *S. foliosa* in TM. There are two 6-8' (1.8 - 2.4 m) round patches of the non-native species, *S. alterniflora*, growing within the pickleweed. This lack of native cordgrass may simply be due to lack of colonization. Dispersal mechanisms for Pacific cordgrass include seeds or vegetative fragments (Josselyn 1983). The nearest source of seed or vegetative fragment to TM would appear to be Cogswell Marsh, located on the other side of the buffer pond. Seed production by cordgrass is, however, limited (Josselyn 1983), and transplanting stems or plugs of cordgrass to establish it in marsh restoration sites is recommended (Zedler, Josselyn and Onuf 1982). An alternative explanation may be that the tidal range (0.08 - 0.69 m), in conjunction with the potentially sluggish tidal flow created by the tide gate, may not be providing enough flushing for the species to establish itself. The use of the tide gate may not only be limiting the amount of tidal influx, but may also be delaying the rate at which the water leaves the marsh. In a natural marsh, water flows in and out along the entire length of the marsh. At TM, water can leave the marsh only through the single tide gate, delaying drainage and potentially prolonging saturated conditions within the marsh. Cordgrass growth can be reduced by tidal inundation which produces saturated conditions arising from sluggish tidal flow or impoundment (Mendelssohn and Seneca 1980; Howes et al. 1981). The amount of water input and duration of water input determines the soil redox potential. The longer a marsh remains wet, the lower the oxygen and nutrient concentrations, and the lower the resulting redox potential, all of which suppress plant growth. Increased flushing and draining brings in more oxygen and flushes out toxins from the root zone that may be inhibiting plant growth (Brenchly-Jackson 1992; Howes et al. 1981). These previous studies suggest that the tidal range at TM may not provide enough tidal flushing for the establishment of *S. foliosa*. The tidal elevation range within TM is similar to the elevational range of cordgrass growth in Alameda (~0.25 - 0.65m) as identified by Callaway and Josselyn (1992). However, TM is only receiving ~25% of full tidal action through the single active tide gate. A third explanation may be that the marsh, at five years of age, is still too young to expect *S. foliosa* colonization, as the plant may take 4 - 8 years or longer before colonizing across its elevational range (Josselyn 1988).

In contrast to Triangle Marsh, SCTM at Shoreline, at 80% tidal action through culverts, appears to be rapidly progressing towards resembling a natural marsh without the limitations of a sluggish tidal flux. The small percentage of vegetation coverage in SCTM can be attributed to the fact that the marsh plain has been allowed to develop naturally and that sedimentation is still occurring. The marsh is still very young and natural sedimentation following re-introduction of tidal action may take 10 - 20 years to reach elevations suitable for colonization by emergent vegetation (Josselyn 1988). Only the southern end of SCTM appears to have reached marsh plain elevations ideal for cordgrass growth. The differences currently present between the marshes at Shoreline may reflect differences in marsh ages (Table 17).

Table 17.--Marsh age and the number of parameters in which the restored marshes at Shoreline showed no significant difference from their natural reference sites, based on statistical analysis

Marsh Name	Marsh Age	Number of Parameters
Mountain View Tidal Marsh	12 years	5 of 7
Stevens Creek Tidal Marsh	3 years	1 of 7

MVTM was restored to full tidal action 9 years before the new culverts were installed at SCTM in 1992. The differences in soils and resulting vegetation may just be a difference in time. Craft, Broome and Seneca (1988) suggested that constructed marshes may take 15-30 years to develop soil characteristics equal to those of natural salt marshes. Future studies monitoring the progress of SCTM should indicate whether the results of this study represent an early stage in the evolution of SCTM towards more closely resembling OCS.

Implications

San Francisco Bay is an area where the natural wetlands have been greatly reduced by filling and development. In areas such as this, there is the hazard that mitigation by marsh restoration may be used as a mechanism by which natural marshes are destroyed one at a time and replaced by habitats of lesser ecological value. Unless the restorations provide replacement habitats that are comparable in the long run to the natural areas of marsh that are destroyed, mitigation by marsh restoration may contribute to further degradation of the Bay.

Restoration has been referred to as the "acid test of ecological theory," because each time we undertake a restoration we are seeing whether we can recreate ecosystems that function properly (Bradshaw 1987). The true test of our understanding of how ecosystems work is our ability to recreate them (Ewel 1987). Restoring an ecosystem involves not only understanding the structure and function of the entire system, but also the individual components that make up the system. In the San Francisco Bay, tidal salt marsh restorationists are frequently given less than ideal conditions under which to conduct a restoration. Factors such as the subsidence of former tidal salt marsh soils, the channelization and control of surrounding watersheds, the proximity of developed lands, limited funding, and strict time schedules have created physical and social pressures on restoration projects which did not exist when the natural marshes were created.

Many salt marsh mitigation projects have had problems due to poor planning, improper implementation, or inadequate knowledge of the functions of the natural system. With recognition of these problems, there has been increasing demand for improved planning, as well as better project implementation and monitoring of restored marsh development (PERL 1990). If restored marshes are to be considered adequate replacements for destroyed natural wetlands, quantitative data must be available documenting the establishment and persistence of vegetation, as well as the marshes' similarity with comparable natural marshes in important biotic and abiotic measures (Race and Christie 1982; Harvey and Josselyn 1986). Since there is limited scientific evidence on the development and stabilization of biotic and physical characteristics of restored salt marshes in the San Francisco Bay (Race and Christie 1982), quantitative studies will aid regulatory agencies in determining if marsh restoration is an acceptable mitigation strategy and may help identify other measures by which to assess marsh restoration success.

Determination of mitigation success depends on the evaluation criteria used. If mitigation projects are mistakenly judged to be successful, then natural resources may be permanently lost. Since the science of marsh restoration is still largely experimental and the long term success of marsh restorations is still in question (Zedler 1988; PERL 1990), it is important to determine which techniques used in restoration and which of the resulting structural and functional characteristics are important components in allowing a restored marsh to more closely resemble a natural marsh.

This study compared measures of primary production, substrate nutrient and salinity characteristics for restored versus natural marshes. Although these data have limitations, including variability in marsh size and differing successional stages of restored sites, the results do provide several useful conclusions.

Because so many factors affect the growth of cordgrass, measuring nutrients and salinity alone does not appear to be completely predicative of the state of cordgrass growth in a marsh. The other factors affecting growth may include inundation levels, substrate redox potential, ion toxicity and marsh plain elevation. However, nutrients and sediment salinity provide useful measures of marsh functioning, as they are still important parameters that influence cordgrass productivity.

Marsh age and tidal flushing appear to be two additional important factors influencing the soil conditions and cordgrass productivity in a restored marsh. At 80% tidal influx, Stevens Creek Tidal Marsh appears to provide enough flushing to maintain a healthy *S. foliosa* population. The low density of cordgrass compared to the natural site may be due to inadequate flushing, but since cordgrass may take 4-8 years before complete establishment (Josselyn 1988), it is probably just a matter of time before the densities increase to levels similar to those at the natural site. The nitrogen levels measured in SCTM indicate that the soil conditions may be moving towards those of the natural site, allowing for potentially greater cordgrass production. Although the differences in NO_3 and NH_4 between SCTM and OCS were statistically significant, NO_3 levels were higher in SCTM, and the average level of NH_4 in SCTM was only 1.1 ppm lower than in OCS.

The lack of cordgrass establishment at Triangle Marsh should, however, be more closely examined. Although it may simply be that colonization has not taken place, other factors may be contributing, such as inadequate flushing as a result of the usage of the tide flap gates, or steep channel slopes within the elevation range of *S. foliosa* growth. Given the age of these two restoration projects and their lack of similarity to natural marshes as shown by this study, agencies monitoring restoration projects should require monitoring for longer than 5 years to adequately assess success of a restoration.

Because cordgrass height and density are both subject to many factors and have been shown to be variable within and between marshes, total stem length should be used to evaluate the success of cordgrass productivity in a marsh restoration. As harvesting of cordgrass within restored marshes may counteract the restoration effort, total stem length provides a non-destructive estimate of biomass. In addition, density and height data individually may be useful in estimating habitat values for specific species, such as the California clapper rail. Since plant height and density may play a factor in determining whether or not certain species chooses to nest in a marsh, such data may be useful in determining habitat function. In southern California, Zedler (1993) explored the nesting requirements of the light-footed clapper rail, an endangered southern California bird. She then compared constructed habitats that lack the bird with natural habitats that support it and selected assessment criteria that best distinguish suitable and unsuitable nesting habitats. She then determined height and density requirements for suitable habitats. Similar assessments for restored marshes in the San Francisco Bay may provide valuable information in determining whether or not restored marshes are providing potential clapper rail habitats.

In addition to habitat value, productivity and nutrient retention functions, the soil and vegetation data may be useful in evaluating other functions such as food chain support. Theoretically, the more biomass produced within a marsh, the more organic matter will enter the soil when the plant parts die. The greater the organic matter, the greater the amount of nutrients and food that gets flushed into the Bay. Total stem length data can be useful in determining the potential amount of food chain support that can be provided by a restored marsh to the Bay ecosystem.

Marshes can be restored to resemble natural marshes with regards to vegetative composition, but the soil and vegetation results from this study indicate that complete functional equivalence is still lacking in all the restored marshes that were examined. However, because the vegetation and soil characteristics were not found to be identical does not necessarily mean that marsh functions do not exist. With lower nutrient levels and lower productivity, these marshes appear to be providing functions at a lower level than the natural marshes. Compared to the equivalency of functions measured in the San Diego Bay constructed marsh (Zedler and Langis 1991), the restored marshes at Shoreline and Hayward appear to be closer to functioning like the natural references. Further studies to more completely test for functional equivalence would include data on faunal community development, such as California clapper rail usage and invertebrate populations, as well as additional substrate physical and chemical characteristics such as organic matter, soil texture and redox potential.

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